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ON THE SELECTION OF MODELING MATERIALS TO SCALE LONG TERM EROSION BEHAVIOR OF PROTOTYPE SYSTEMS

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13. ABSTRACT

Attempts are now being made to develop modeling techniques to scale the intensity of erosion in the laboratory. This paper deals with the quantitative aspects of the selection of modeling materials. The major problem is the relationship between the rate of erosion and the exposure time. The erosion rate-exposure time relationships for a spectrum of materials are correlated with a recently developed theory of erosion. This approach shows how one could relate model-prototype materials quantitatively. Practical feasibility and limitations are also discussed.

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Technical Report 71-1

On The Selection of Modeling Materials to Scale Long Term Erosion Behavior of Prototype Systems

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NOTATION

I_e	Intensity of erosion - Power absorbed by the unit eroded area of the material - Watts/Meter^2
S_e	Erosion strength - Newton/Meter^2
r	Mean depth of erosion - Meter
t	Exposure time - seconds
$r_{max} = (\frac{dr}{dt})_{max}$	Maximum rate of erosion - Meter/second
t_1	Exposure time corresponding to the maximum rate: also called the characteristic time - seconds
I_c	Intensity of bubble collapse - Watts/Meter^2
I_i	Intensity of impact - Watts/Meter^2
η	Efficiency of power absorption in the material - dimensionless
A	A proportionality constant with length dimension - meter
n	The attenuation exponent - dimensionless
r_c	The distance between the original surface of material and the center of bubble - meter
α	Shape parameter - dimensionless
$c_1(\alpha)$	A constant depending on shape parameter - dimensionless

SUMMARY

Cavitation erosion is one of the major problems confronting the designers of modern high speed hydrodynamic systems. Usually these systems are required to operate trouble free for more than 10,000 hours. The current practice is to select the most erosion resistant material that meets the structural and fabrication requirements economically. However, the recent trend is toward higher operational speeds. At such higher speeds, the intensity of erosion at localized areas has in some cases, overcome the erosion resistance of even the most resistant materials. Such situations can be avoided in the future designs if one could estimate the level of intensity of erosion for his design at the designing stage itself by means of model tests. This would lead to the necessary modifications to a design so that the intensity levels are within the capability of the candidate materials selected for the design.

It is now well established that the rate of erosion is very much dependent on the exposure time. This makes the estimation of prototype performance over a long period of time difficult mainly because the laboratory test must necessarily be of a short duration test using perhaps a weaker material. Although many hurdles are to be overcome before such a procedure becomes a practical reality, some attempts have been initiated toward a scientific study of this problem. It is the purpose of this paper to present such studies made on a spectrum of materials ranging from aluminum to stainless steel in a vibratory cavitation erosion apparatus. The erosion time histories for these materials vary over a time scale ranging from a few minutes to a few days. Such a wide range of data is correlated with a recently developed theory of erosion. This approach of combining theory and experience leads to a very useful understanding of the interacting roles of several parameters.

For example, the time at which the maximum intensity of erosion occurs on a given metal is predictable if one knows the shape parameter and the erosion strength for the material. It is also possible to estimate the cumulative depth of erosion on a candidate material if one knows the erosion history of the given design using a modeling material. These results are discussed in detail with the supporting experimental evidence for the spectrum of engineering materials. Practical feasibility and limitations of this approach in model-prototype correlations are discussed.

INTRODUCTION

Cavitation erosion is one of the serious problems in high speed hydrodynamic systems. Recent experiences with prototype systems show that, in some cases, the intensity of erosion may be so severe that even the most resistant material will be eroded in a relatively short operation. In such situations it becomes apparent that basic changes in the hydrodynamic design are needed to reduce the intensity of erosion at the critical areas. This necessitates the development of modeling techniques to verify the proposed design changes in the laboratory. There are many problems to be solved before any acceptable modeling technique is established. One is the relation between the resistance of the material used in the laboratory model and that used in the prototype system. Usually the prototype systems are required to operate for a long time (greater than 10,000 hours) trouble free. Assuming that the hydrodynamic conditions may be simulated at the laboratory to produce the same intensity of erosion, it becomes essential to use a weaker material in the laboratory model so that the testing time can be reduced to an economically acceptable value. One of the primary objectives of this paper is to explore this possibility.

By now, it is well established that the rate of erosion is a function of the exposure time. It was known to hydraulic engineers that cavitation erosion decreased with repeated exposure of the hydraulic structures to floods (1). Thiruvengadam (2,3) noticed the decreasing trend in erosion with continued exposure. Hobbs (4) as early as 1962 reported this effect. Investigators (5) working on the problem of rain erosion noticed the nonlinear dependency with exposure time as early as 1957. These evidences led Thiruvengadam and his co-workers (6,7,8,9) to conduct a series of systematic experiments on these effects. The essential conclusion was that it is important to consider these effects both in comparing different materials and in extrapolating the laboratory experience to field systems. These studies stimulated an intensified research activity in this area. Hobbs (10), Plesset and Devine (11), Heymann (12), Hammitt and his co-workers (13,14,15), Ripken (16), Rao et. al. (17), Tichler (18) and Canavelis (19) among others have made significant contributions in understanding the various aspects of this phenomenon.

The erosion history may be divided into four periods*, figure 1 as follows:

1. Incubation period
2. Acceleration period
3. Deceleration period
4. Steady period

Several exceptions to this general trend are reported in the literature. For example, Hammitt and Garcia (20) reported that there are in fact two acceleration periods in some cases. Hobbs (10) found that there is a steady period in between the acceleration period and the deceleration period. The experiments on 4340 steel by Plesset and Devine (11) as well as the experiments by Tichler et al (18) on chromium steel show that this is indeed the case. However, in all our vibratory experiments using a wide range of materials** (including 1100-F aluminum, 2024 aluminum, tobin bronze, commercially pure nickel, monel, 316 stainless steel and SAE 1020 steel) we did not find a truly steady period in between the acceleration and deceleration periods as shown in figures 2 through 8. This is also true in our experiments with liquid sodium at various temperatures. For some stronger materials such as 316 stainless steel and 4340 steel, the transition from the acceleration period to the deceleration period takes place over a longer time interval and one could approximate it to be a steady period for the purpose of analyses.

Except for these variations, it is now generally accepted by most of the investigators that these effects are indeed true and important. Figure 9 shows a log-log plot of all the data contained in figures 2 through 8. According to this figure, the erosion rates as well as the exposure times to cover all the four periods vary over two orders of magnitude. If we include more resistant materials such as stellites, then the range of erosion rates and erosion times would vary over three orders of magnitude as pointed out by Heymann (21).

*These terms correspond to the recently developed definitions by the ASTM Sub-Committee headed by Dr. Robert Hickling.

**It is important to note that these materials include two pure metals, one carbon steel, one stainless steel and three different alloys.

If the relationship between various materials during the four erosion periods, extending over such a wide range, can be quantitatively established, then it is indeed possible to conduct experiments in the laboratory in a shorter period of time using a weaker material and to infer the behavior of more resistant material in the field. This is precisely the objective of this paper. An attempt has been made to use the erosion theory recently developed by the author (9) to accomplish this objective. The usefulness as well as the limitations of this approach are also discussed.

CORRELATION OF EXPERIMENTAL DATA WITH THE ELEMENTARY THEORY

The experimental data shown in figures 2 through 9 is all reduced in a non-dimensional form first introduced by the author in 1966 (9). The experimentally determined erosion rate (in any form such as rate of weight loss, rate of volume loss and rate of mean depth of erosion) is divided by the peak rate of erosion to get the relative rate of erosion. The relative rate of erosion is the same as the relative intensity of erosion if we assume that the area of erosion as well as the erosion strength of the material remains constant during a given test. Even if one does not believe in any theory, this non-dimensional plot is physically significant since one can compare the relative behavior of different materials at a given intensity of erosion as well as the behavior of the same material at different intensities. The discussion by Hammitt and Garcia (20) contains an idea similar to this. This is an important step toward quantitative correlations. The relative erosion rate is plotted against the relative exposure time in figure 10. The relative exposure time is obtained by dividing the exposure time by the characteristic time, t_1 corresponding to the peak rate.

There is a certain amount of subjective decision involved in selecting the peak erosion rate and the characteristic time. However, standard numerical techniques with the aid of modern computers may be used in determining the erosion rates more rationally. One such method* is the five point averaging technique described by Hildebrand (22) which leads to a more objective determination of the peak rate and the characteristic exposure time.

*The author is grateful to Dr. A. F. Conn of Hydronautics Incorporated for suggesting this method.

Figure 10 shows that the relationship between the relative erosion rate (and hence the relative intensity of erosion) and the relative exposure time is very nearly the same for all the materials considered in this paper. For example, the erosion rates on all these materials would reduce to almost 40 percent of the peak rate after exposing them for a relative exposure time of about five. If we can relate the peak rates and the corresponding exposure times for a modeling material as well as the prototype material, then we will be able to estimate the performance of the prototype material from the behavior of the modeling material at a corresponding intensity of erosion. This is where we need a quantitative theory that would correlate with experimental data shown in figure 10.

There have been several attempts to explain the erosion history quantitatively, the foremost being that of Heymann (12) followed by Thiruvengadam (9) and Mok (23). For the purposes of this paper, we will make use of the elementary theory developed by the author (9). The important equations derived from this theory are briefly summarized in the Appendix of this paper. According to this theory, the erosion rates and the exposure times are also normalized with respect to the conditions at the peak rate of erosion. Equation /A 7/ gives the relative intensity of erosion (and hence relative rate of erosion) as a function of the relative exposure time. Using a value of 2 for the attenuation exponent and assuming Weibull type distributions* for the efficiency function, the relative intensity of erosion can be calculated. Figure 11 shows this relationship for various values of the shape parameter (9, 25). By inspection, it is found that the data in figure 10 best fits the curve corresponding to the shape parameter, $\alpha = 1.5$. In this sense, this is actually a curve fitting procedure.

Now that we have determined the value of α, we can proceed further to make use of the theoretical equations shown in the appendix to determine the peak rates and the corresponding times. The relationship between the erosion

*The use of Weibull type distributions is questioned by Heymann both in private discussions and in the discussion of Reference (24) which contains complete details. It must be pointed out that this controversy does not limit the use of this theory for practical applications.

strength and the other parameters is given by equation [A 18] as

$$S_e = \frac{0.33 \quad \alpha^2 \quad C_1^3 \;\; A^2 I_c \; t_1}{r_1^3} \qquad \text{(See Appendix Eqn. A 18)}$$

where

α is the shape parameter

C_1 is a constant given by equation [A 13] and depends only on α

r_1 is the cumulative mean depth of erosion corresponding to the peak rate of erosion,

t_1 is the exposure time corresponding to the peak rate of erosion and is called the characteristic time

and $A^2 I_c$ is a constant for a given input intensity of erosion governed by the bubble collapse energy.

For practical purposes, let us assume that the value of the shape parameter is a constant for the materials considered in figure 10. Later on we shall consider the variations in the shape parameter. From equation [A 13], C_1 is solely a function of α and is a constant if α is a constant. According to the original assumption represented by equation [A 2], the value of $A^2 I_c$ represents the intensity of the bubble cloud and is constant for a given test condition.

At this juncture, it is useful to review some of the experimental facts concerning the cumulative mean depth, r_1. Heymann (26) in 1965 reported the results of Hobbs at the National Engineering Laboratory and of Pearson at CEGB Marchwood Engineering Laboratories, both in the United Kingdom; the total volume loss per unit eroded area up to the start of the attenuation period was the same for all metals tested by them. In other words, the cumulative mean depth (which is total volume per unit eroded area divided by the density of the material) corresponding to the peak was a constant. This result seemed to be significant and indicated that a certain mean depth of erosion caused the attenuation in all the metals. An analysis of our results confirms the earlier British work. Table 1 shows that r_1 (the cumulative mean depth of erosion corresponding to the peak rates) for the seven materials considered in this paper remains constant with a maximum deviation of 13 percent. Based on these evidences, we can conclude that r_1 is a constant.

Now then, the only variable in equation /A 18/ is the characteristic time, t_1. According to equation /A 18/, the characteristic time, t_1 should be directly proportional to the erosion strength, S_e. The question is: What is erosion strength? This has led to much controversy in recent years (27) and many investigators have considered this question in detail.

Table 1 Cumulative Mean Depth of Erosion Corresponding to the Peak Rate of Erosion

Material	Total Volume Loss up to peak rate of erosion - cm^3	Cumulative Mean Depth of erosion cm	Percent Derivation from Mean
1100-F Aluminum	$10.80X10^{-3}$	$6.9X10^{-3}$	-1
2024 Aluminum	$11.70X10^{-3}$	$7.4X10^{-3}$	+5
Tobin Bronze	$10.21X10^{-3}$	$6.5X10^{-3}$	-8
Nickel	$12.06X10^{-3}$	$7.6X10^{-3}$	+9
Monel	$11.71X10^{-3}$	$7.4X10^{-3}$	+5
1020 Steel	$11.38X10^{-3}$	$7.2X10^{-3}$	+2
316 Stainless Steel	$9.59X10^{-3}$	$6.1X10^{-3}$	-13

CONTROVERSIES ABOUT THE STRAIN ENERGY AS THE BASIS OF EROSION STRENGTH

During the late fifties, Rao and Thiruvengadam (28) investigated the relationship between erosion resistance and the various mechanical properties of a group of commercially pure aluminum with different hardness. It was found that the rate of erosion was inversely proportional to all of the mechanical properties such as yield strength, ultimate strength, and hardness. This was no surprise since these mechanical properties were related to each other.

Then Thiruvengadam (3) investigated a group of materials whose mechanical properties were not related in any systematic manner. He found that the erosion rate did not correlate with any of the common mechanical properties in contrast to the aluminum group. Arguing that the volume eroded must be related to some energy parameter of the material, he found that the erosion rate correlated much better with strain energy. Extending this idea further, Thiruvengadam and Waring (29) again confirmed that strain energy was a much better correlating parameter.

Young and Johnson (30) found a good correlation with strain energy with the exception of Stellite 6B. It is significant that they conducted their experiments systematically to avoid the interacting influence of exposure time. Hobbs (10) using the peak rate of erosion as the criterion came to the conclusion that the material's capacity to store elastic energy in deformation (called ultimate resilience) was the best correlating parameter for a group of tool steels. Hammitt and his coworkers (31,13,14) have done considerable research on a wide range of materials tested in different test equipments over these years. They have concluded that no single property can offer the best choice although Hammitt (31) has recently advocated the ultimate resilience as the most promising parameter. It is important to note that all these investigators accept the premise that some energy parameter represents the erosion resistance.

Recently, Tichler et al (18) have found that the true tensile strength is the most important parameter for a group of fourteen chromium steel while Rao et al (17) prefer the product of ultimate resilience and brinell hardness. Heymann (21) has concluded that a new parameter given by (ultimate tensile strength)^2 x modulus of elasticity is the best correlating parameter for a broad range of materials tested by various investigators.

It appears from this review that we are back again where we started in the attempt to correlate erosion resistance with material properties. Realizing such a possibility, Thiruvengadam (32) suggested during the 1965 ASTM Symposium that we define an erosion strength in its own right and determine its value from an erosion test. He used the strain energy for a few standard materials as the basis. These standard materials are among the materials considered in this paper. Let us see how the characteristic time, t_1, is related to the strain energy of these materials. Figure 12 shows a plot of t_1 against the strain energy. Each data point is enclosed in a shaded area which represents the scatter zone both for t_1 and for strain energy. Since both are experimental quantities, they do vary over a range represented by the shaded area. Figure 12 does show a general trend which is good enough for practical purposes. However, one may find a better correlation by taking into account the variations in the shape parameter, α . For example, the shape parameter for SAE 1020 steel is nearly 2 whereas that for 2024 aluminum

is about 1. According to equation /A 18/, the erosion strength depends both on α^2 and on $C_1^3(\alpha)$. The functions $C_1(\alpha)$ and $\alpha^2 C_1^3(\alpha)$ are plotted in figure 13.

These correlations do indicate that the strain energy is a good material parameter for at least a few commonly used materials. However, it may not be a unique property that represents the erosion resistance of all materials. In fact it need not be. It is enough if it serves as the basis for a few calibrating materials. The same argument holds well for any other property such as ultimate resilience and tensile strength. The combination of mechanical properties will complicate the dimensional balance of the equations. With these few remarks, let us leave it to the personal preference of the investigator to choose his scale for the erosion strength. Equation /A 18/ lends itself to a free choice of the erosion strength which will determine the value of $A^2 I_c$ for given test equipment and test parameters.

MODEL-PROTOTYPE CORRELATIONS

In order to apply these ideas for correlating a model and its prototype, one would start testing the model material and the prototype material in a standard screening apparatus such as a vibrating apparatus*. From such a test, the values of S_e, α and C_1 for both materials will be known. Then the model test may be carried out from which the values of r_1, t_1 and hence, $A^2 I_c$ can be determined. Since the model is supposed to simulate the cavitation environment**, the value of $A^2 I_c$ would be the same both for model and prototype. Using equation /A 18/ we can calculate the value of t_1 for the prototype material, assuming r_1 to be the same for both. From equation /A 17/, we can calculate the maximum intensity of erosion. Once we know the values of Imax, t_1 and α, we can generate the entire erosion curve for the prototype material using this theory. While these ideas offer exciting possibilities, the success of this approach is yet to be demonstrated by actual model prototype experience.

*It is noteworthy that the ASTM Committee, G-2 on Erosion is presently engaged in standardizing the vibrating apparatus.

**Problems involved in the simulation of the prototype cavitation environment in a model are discussed by the author elsewhere (33,34).

The data presented in this paper was collected at an intensity level of about one watt/meter^2. Even the stainless steel is eroded substantially in about 50 hours. However, if a prototype system were to operate for 10,000 hours or more, the intensity should be less than a hundredth of a watt/meter^2. There is a need for a systematic study of such low intensities of erosion. Hammitt (36) pioneered work in this area as early as 1962 using a Venturi cavitation apparatus in the laboratory. However, such studies should be coordinated with prototype performance in the field over a long exposure period.

In addition, the operating conditions (such as speed, load and depth or pressure) of the prototype may vary during its life either systematically or at random depending on the prototype's mission. This is an important limitation to any quantitative approach. The experience and judgment of the designer plays a very important role in this case.

CONCLUDING REMARKS

It has been demonstrated in this paper that it is possible to consider the relationship between the rate of erosion and the exposure time in a quantitative manner for a range of materials. This offers a possibility of using a weaker material to learn about the erosion potential of a practical system constructed from a more resistant material. This is particularly significant for systems required to operate trouble free for well over 10,000 hours. The ideas presented in this paper are fairly simple and easily usable.

The selection of materials for the model will be governed by several requirements such as structural strength, environmental effects, reproducibility of results and techniques employed in the manufacture of the models in addition to the considerations involving test duration.

For systems operating at a fairly high intensity of erosion (consequently short-life systems), it is economical and convenient to use the actual prototype material in the model. This is justified because the model life as well as the prototype life will be short at high intensities of erosion.

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APPENDIX - DERIVATION OF EQUATIONS USED IN THIS PAPER

(See references 9 and 25 for full details).

The intensity of erosion is defined as

$$I_e = S_e \frac{dr}{dt} \qquad [A\ 1]$$

where I_e is the intensity of erosion,

$\frac{dr}{dt}$ is the instantaneous rate of erosion, at any time, t

S_e is the erosion strength

and r is the mean depth of erosion as measured from the original surface of the material. Furthermore, the following two assumptions are made:

The intensity of impact on the surface is assumed as

$$I_i = \frac{A^n\ I_c}{(r + r_c)^n} \qquad [A\ 2]$$

where

I_i is the intensity of impact

I_c is the intensity of collapse or collision

A is a proportionality constant with length as dimension

n is the attenuation exponent

and r_c is the distance between the original surface of material and the center of bubble.

The second assumption is

$$I_e = \eta\ I_i \qquad [A\ 3]$$

where η is a material property governing the efficiency of energy absorption and varies with the exposure time. Combining equations [A 1], [A 2] and [A 3], we can derive the differential equation of erosion.

$$\frac{dI_e}{dt} + \frac{KI_e^{(2n+1)/n}}{(\eta)^{1/n}} - \frac{I_e}{\eta}\frac{d\eta}{dt} = o \qquad [A\ 4]$$

$$\text{where } K = \frac{n}{S_e(A^n I_c)^{1/n}} \qquad [A\ 5]$$

This equation can be normalized with respect to the parameters corresponding to the maximum intensity of erosion.

At $t = t_1$;

(t_1 is called the characteristic time.)

$$\begin{cases} I_e = Imax \\ \dfrac{dI_e}{dt} = o \\ \eta = \eta_1 \end{cases}$$

Then relative exposure time, $\tau = \dfrac{t}{t_1}$,

relative intensity of erosion $\bar{I} = \dfrac{I}{Imax}$,

relative efficiency $\bar{\eta} = \eta/\eta_1$

and relative rate of erosion $= \dfrac{\dot{r}}{\dot{r}max}$

where the dot represents the derivative with respect to time. Using these normalized values, equation [A 4] becomes

$$\frac{d\bar{I}}{d\tau} + \frac{\bar{K}\,\bar{I}^{\frac{(2n+1)}{n}}}{(\bar{\eta})^{1/n}} - \frac{\bar{I}}{\bar{\eta}}\frac{d\bar{\eta}}{d\tau} = o \qquad [A\ 6]$$

$$\text{Where } \bar{K} = \frac{K\,Imax^{\frac{n+1}{n}}\,t_1}{(\eta_1)^{1/n}} = \left.\frac{d\bar{\eta}}{d\tau}\right| \text{ at } \tau = 1$$

The general solution of this normalized equation is given by

$$\bar{I} = \frac{\bar{\eta}}{\left[1 + \frac{3}{2}\bar{K}\int_1^{\tau}\bar{\eta}\,d\tau\right]^{2/3}} \qquad [A\ 7]$$

when n = 2.

Again if we assume that η is of the Weibull type probability distribution functions, then

$$\eta = 1 - \exp(-\tau)^{\alpha} \qquad [A\ 8]$$

$$\eta_1 = \frac{e - 1}{e} = 0.635 \qquad [A\ 9]$$

$$\bar{\eta} = 1.58\ (1 - \exp(-\tau)^{\alpha}) \qquad [A10]$$

and $\bar{K} = 0.58\,\alpha$ $\qquad$ [A11]

The cumulative depths of erosion at any exposure time may be derived as follows:

$$\bar{I} = \frac{I_e}{Imax} = \frac{S_e}{Imax} \cdot \frac{dr}{dt} \; ; \; Imax = S_e \cdot \left(\frac{dr}{dt}\right)_{max}$$

at $\quad t = t_1,\ r = r_1;\ \bar{r} = \frac{r}{r_1}\ ;\ \tau = \frac{t}{t_1}$.

Then $\bar{I} = \dfrac{S_e}{Imax}\ \dfrac{r_1}{t_1}\ \dfrac{d\bar{r}}{dt}$ and

$$\frac{S_e r_1}{Imax\ t_1} \quad \bar{r} = \int_0^{\tau} \bar{I}\ d\tau \qquad [A12]$$

Again at t_1, $\tau = 1$ and $\bar{r} = 1$

$$\frac{S_e r_1}{Imax\ t_1} = \int_0^{\tau} \bar{I}\ d\tau \qquad [A13]$$

Then

$$\bar{r} = \frac{\int_0^{\tau} \bar{I}\ d\tau}{\int_0^{\tau} \bar{I}\ d\tau} \qquad [A14]$$

Considering equations [A 7] through [A 11], the function $\bar{I}\ d\tau$ is solely dependent on the shape parameter, α . The definite integral in equation [A 13] is a constant for a given value of α .

$$\int_0^{\tau} \bar{I}\ d\tau = C_1(\alpha) \qquad [A15]$$

The values of $C_1(\alpha)$ are shown in figure 13.
Using equations /A 5/ and /A 8/ through /A 11/, we get

$$\frac{2}{(A^2 I_c)^{\frac{1}{2}} S_e} = \frac{\dot{I}max^{-\frac{3}{2}} \left(\frac{e-1}{e}\right)^{\frac{1}{2}} \alpha}{t_1 (e-1)} \qquad /A16/$$

Simplifying and rearranging

$$S_e = \frac{0.33\ A^2 I_c\ \alpha^2}{t_1^2\ (\dot{r}max)^3}$$

From equations /A13/ and /A15/

$$\dot{r}_{max} = \frac{r_1}{t_1 C_1} \qquad /A17/$$

Then $$S_e = \frac{0.33\ A^2 I_c\ \alpha^2 C_1^3 t_1}{r_1^3} \qquad /A18/$$

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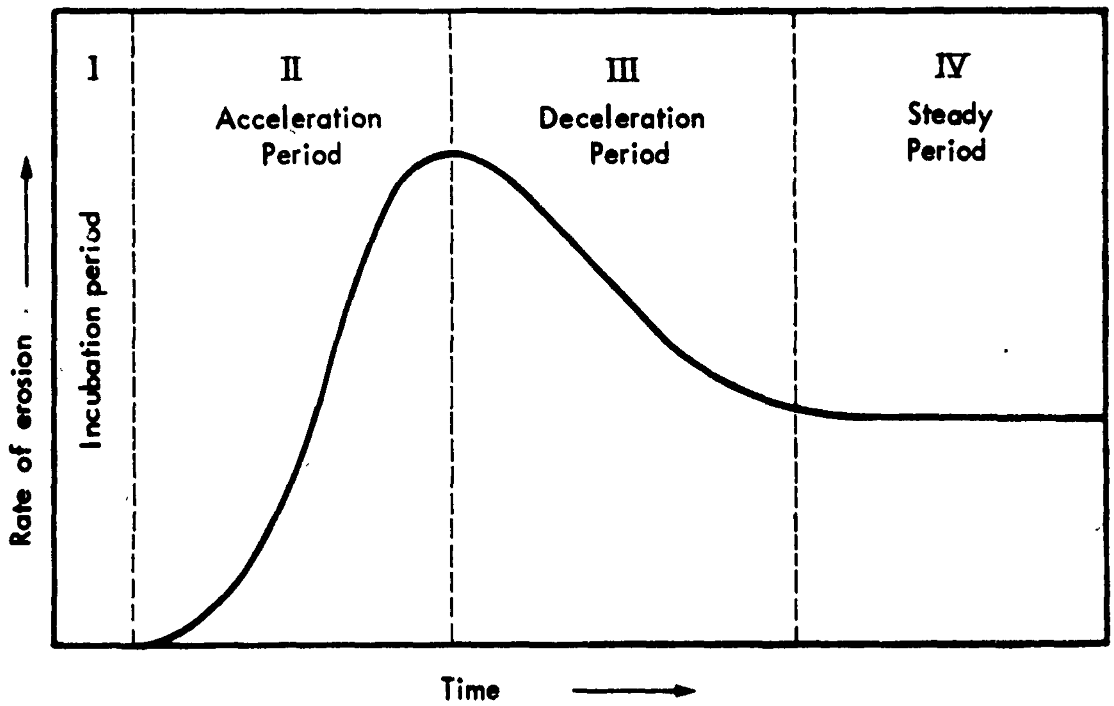

Figure 1 - Classification of erosion periods.

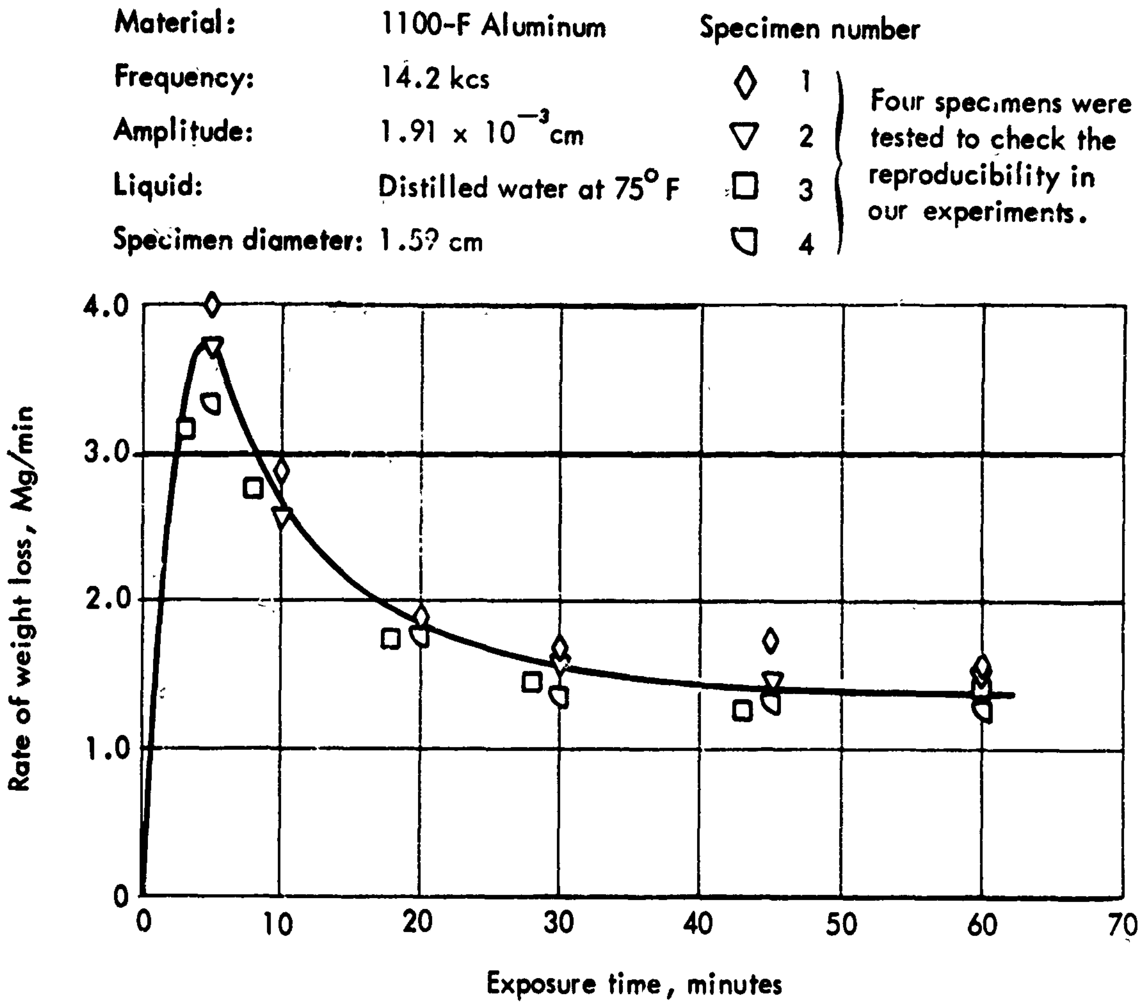

Figure 2 - Relation between exposure time and cavitation erosion rate of 1100-F aluminum.

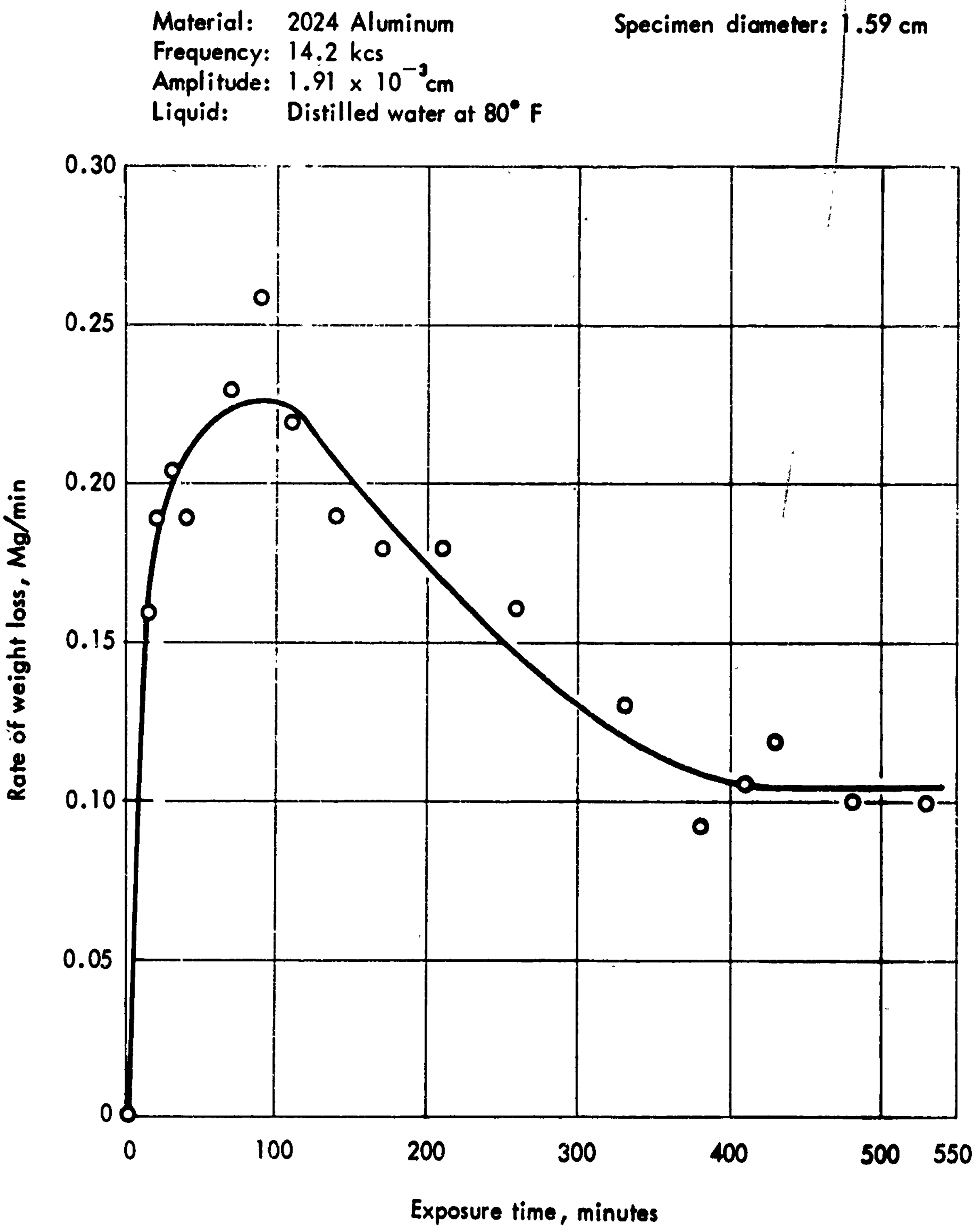

Figure 3 - Relation between exposure time and cavitation erosion rate of 2024 aluminum.

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Material: Tobin bronze

Frequency: 14.2 kcs

Amplitude: 1.91×10^{-3} cm

Liquid: Distilled water

Specimen diameter: 1.59 cm

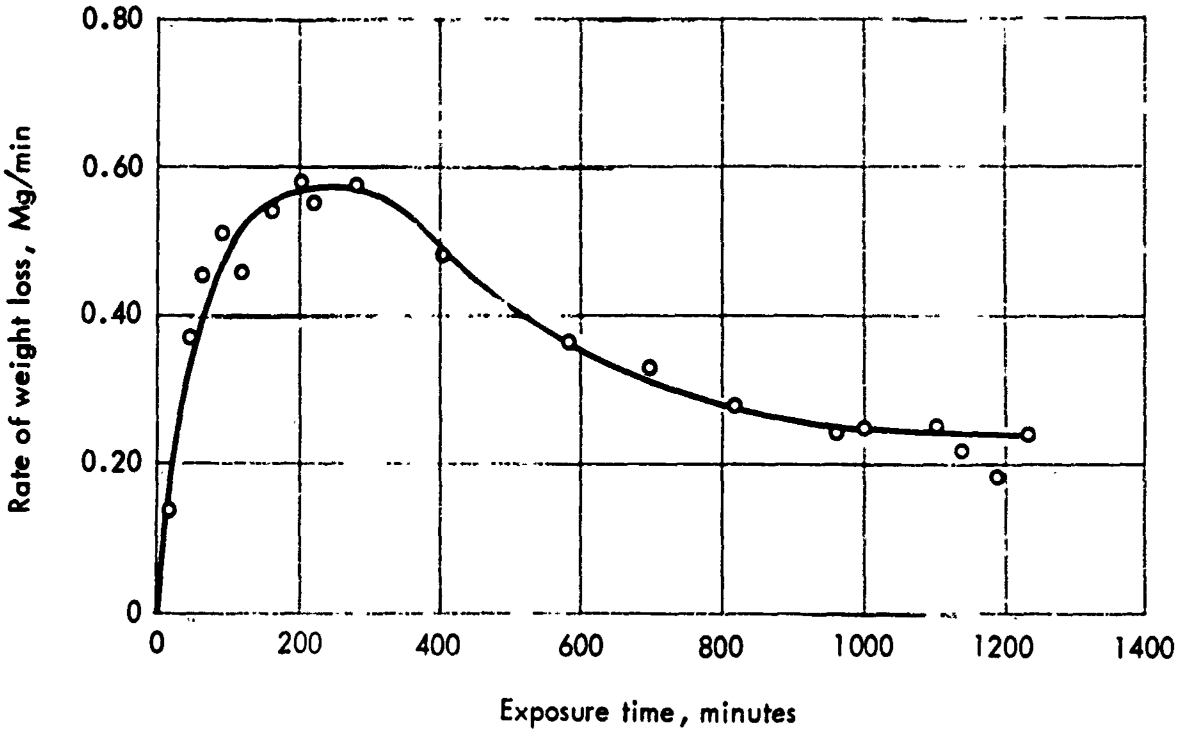

Figure 4 - Relation between exposure time and cavitation rate of tobin bronze.

Material: Nickel (Commercially pure)

Frequency: 14.2 kcs

Amplitude: 1.91×10^{-3} cm

Liquid: Distilled water at 75° F

Specimen diameter: 1.59 cm

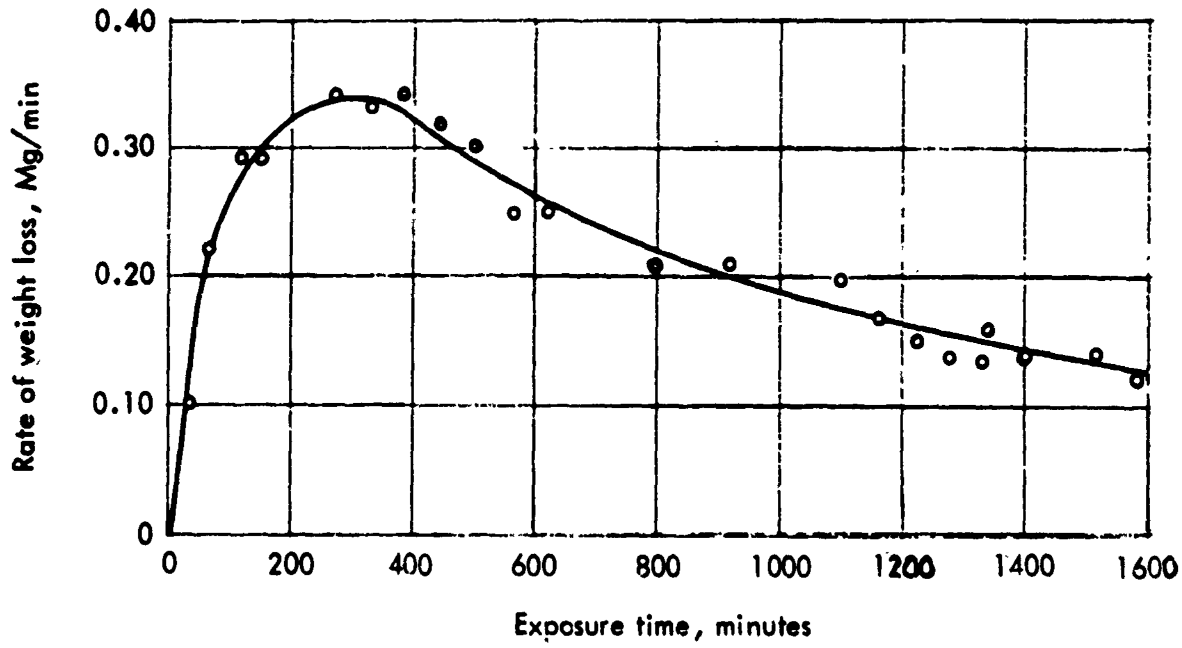

Figure 5 - Relation between exposure time and cavitation erosion rate of nickel (commercially pure).

Material:	**Monel**
Frequency:	**14.2 kcs**
Amplitude:	**1.91×10^{-3} cm**
Liquid:	**Water at 75° F**
Specimen diameter:	**1.59 cm**

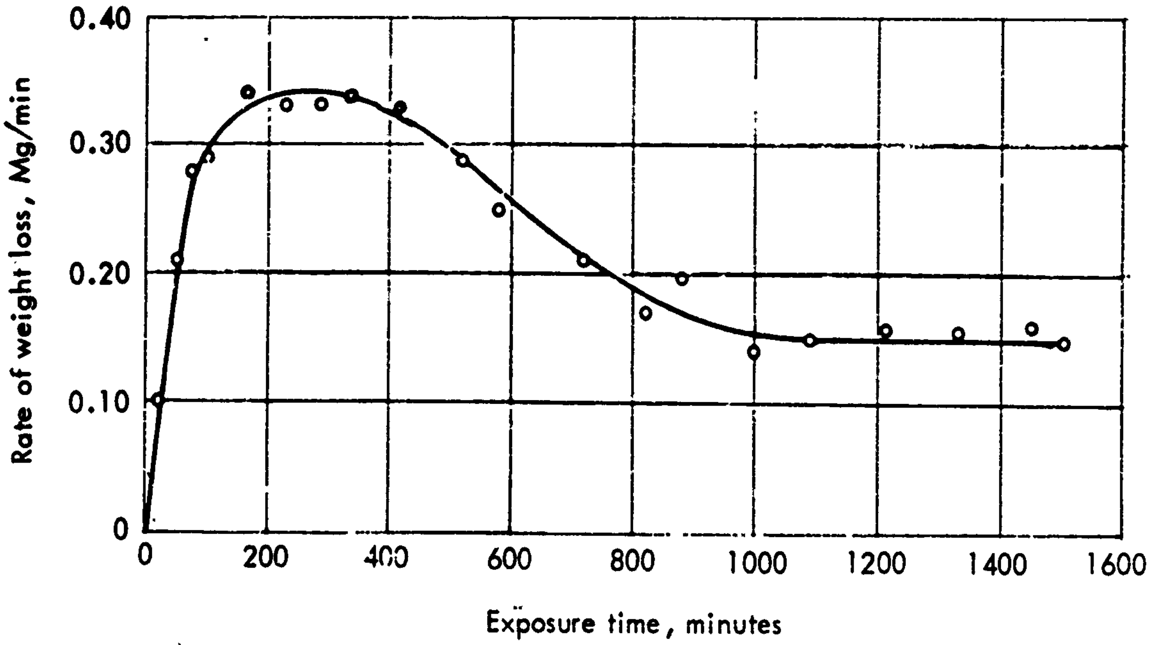

Figure 6 - Relation between exposure time and cavitation erosion rate of monel.

Material: 1020 Steel
Frequency: 14.2 kcs
Amplitude: 1.91×10^{-3} cm
Liquid: Distilled water at 75° F

Specimen diameter: 1.59 cm

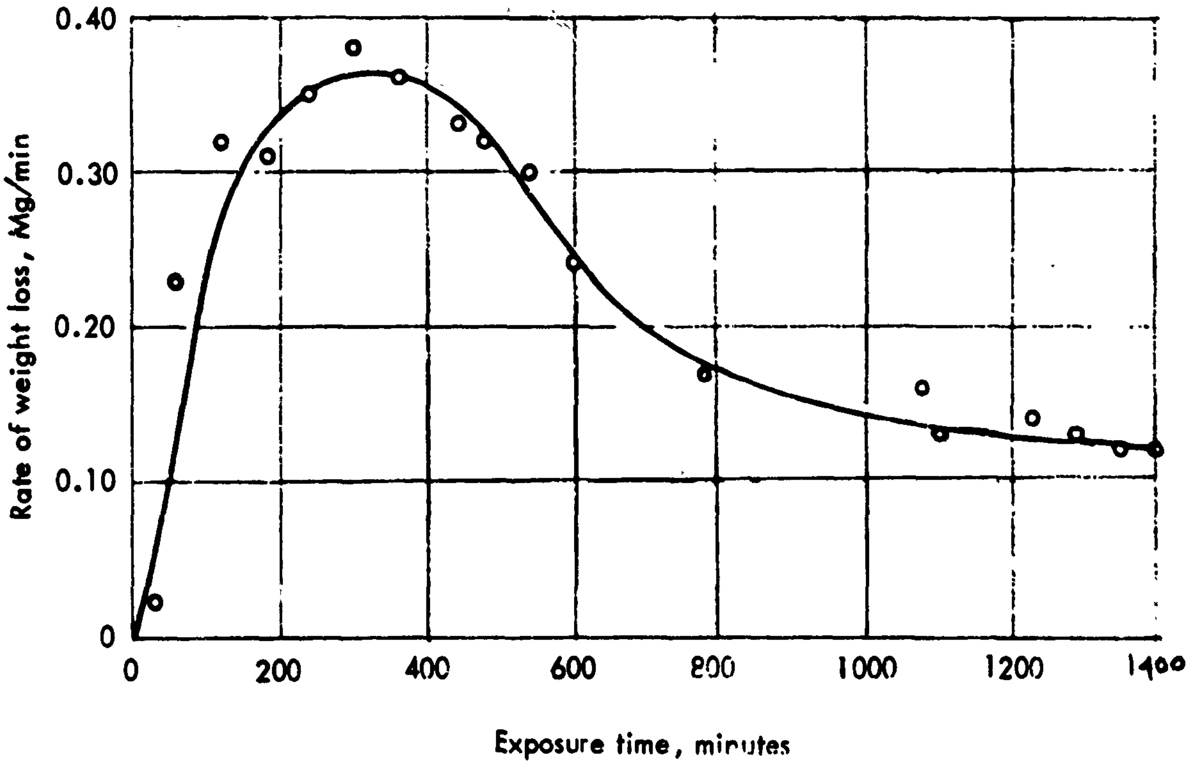

Figure 7 - Relation between exposure time and cavitation erosion rate of SAE 1020 steel.

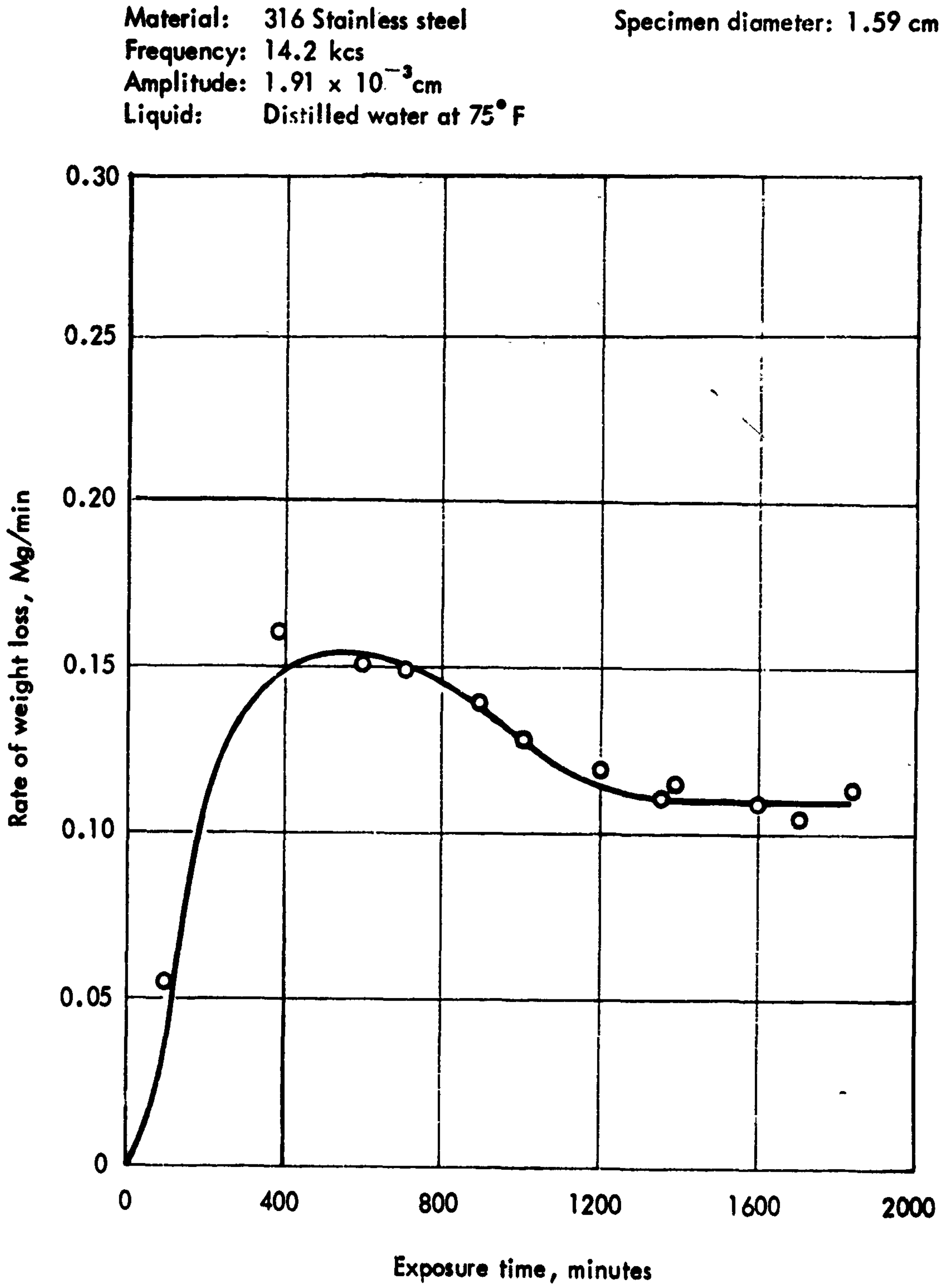

Figure 8 - Relation between exposure time and cavitation erosion rate of 316 stainless steel.

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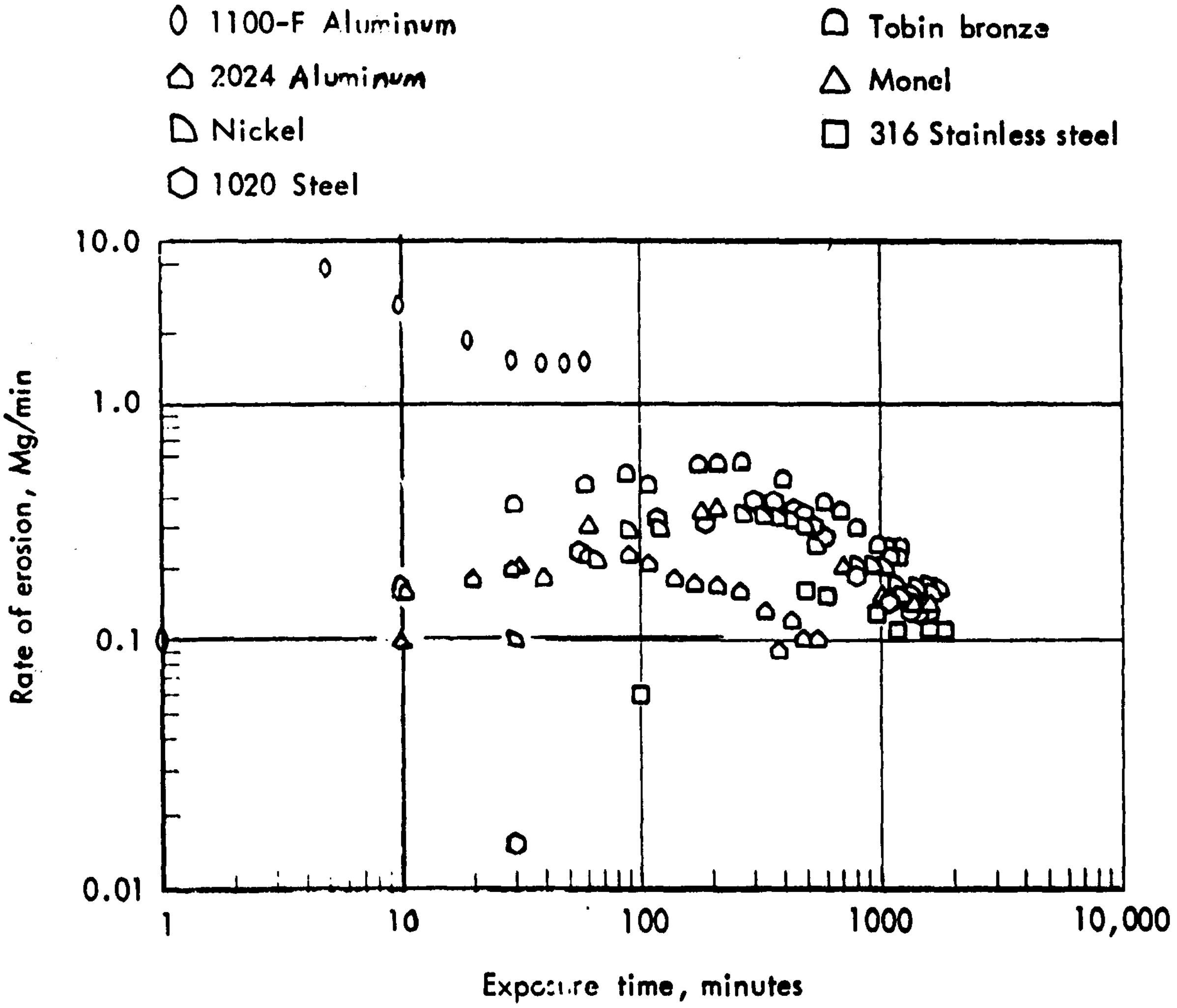

Figure 9 - Comparison of erosion rate and exposure time for seven materials.

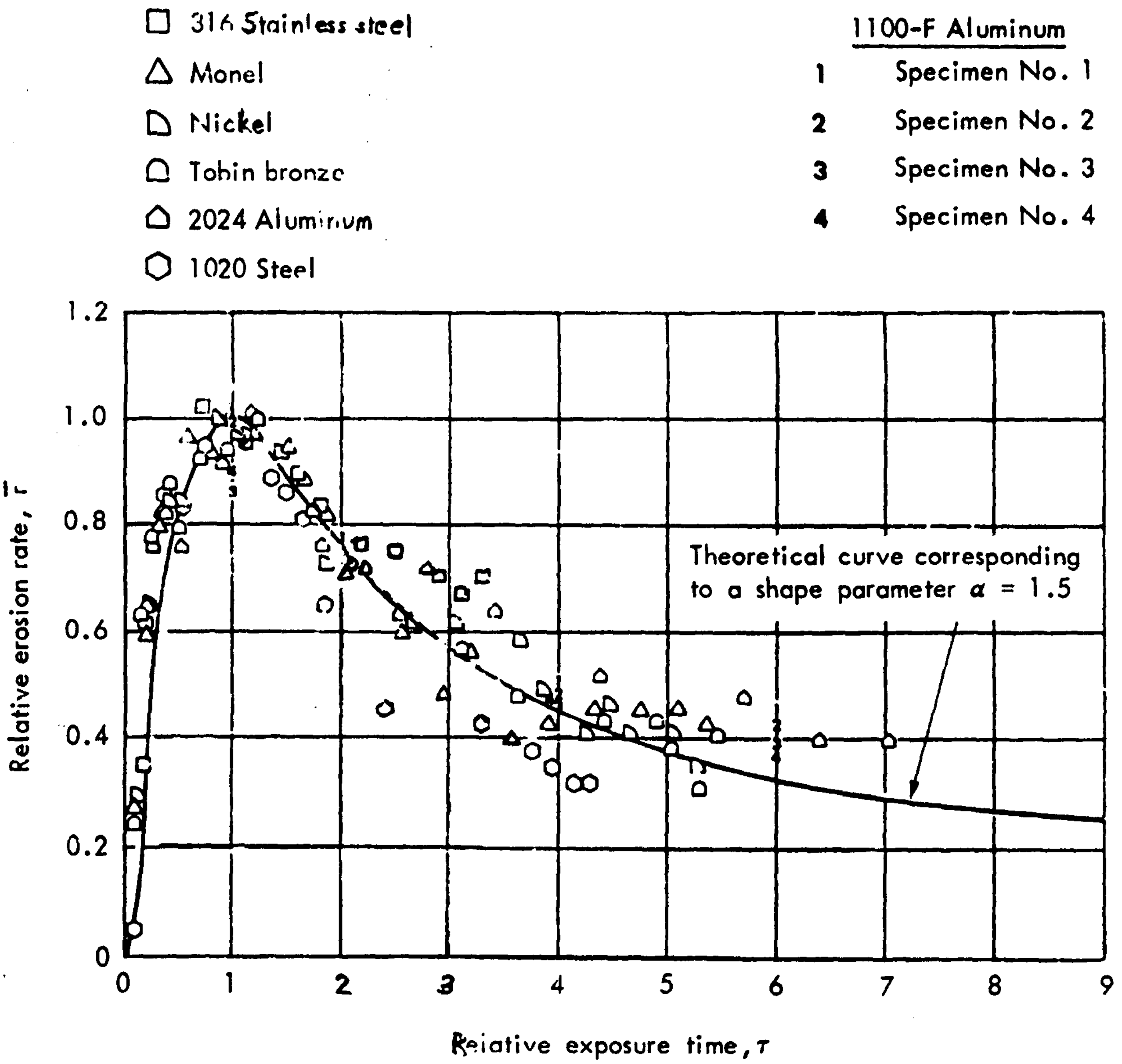

Figure 10 - Relative erosion rate as a function of relative exposure time for the seven materials.

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$$\ddot{I} = \frac{\bar{\eta}}{\left[1 + \frac{3}{2}\bar{k}\int_{1}^{\tau} \eta \, d\tau\right]^{2/3}}$$

Weibull Distribution

$$\eta = 1 - \mathrm{Exp}\left[-\tau^{\alpha}\right]$$

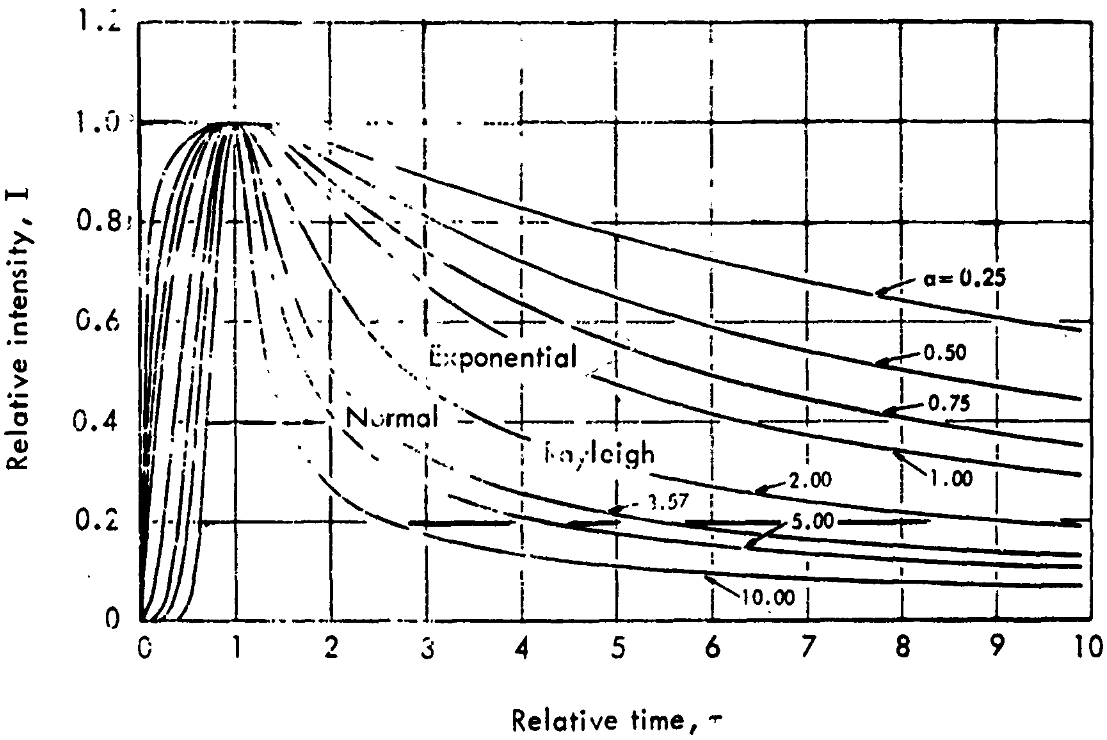

Figure 11 - Theoretical prediction of the effect of time on intensity of erosion when n = 2.

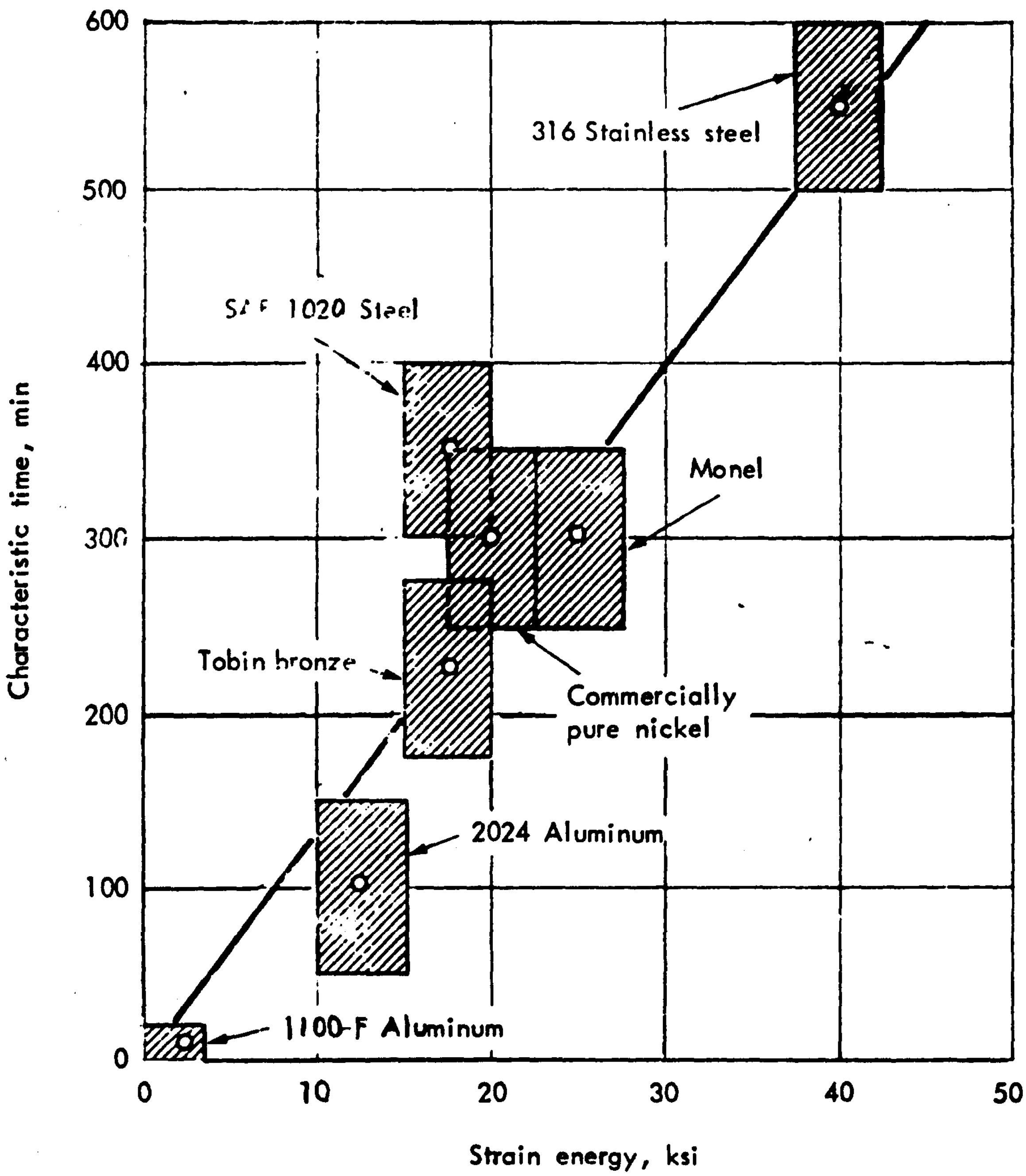

Figure 12 - Relation between characteristic time and strain energy.

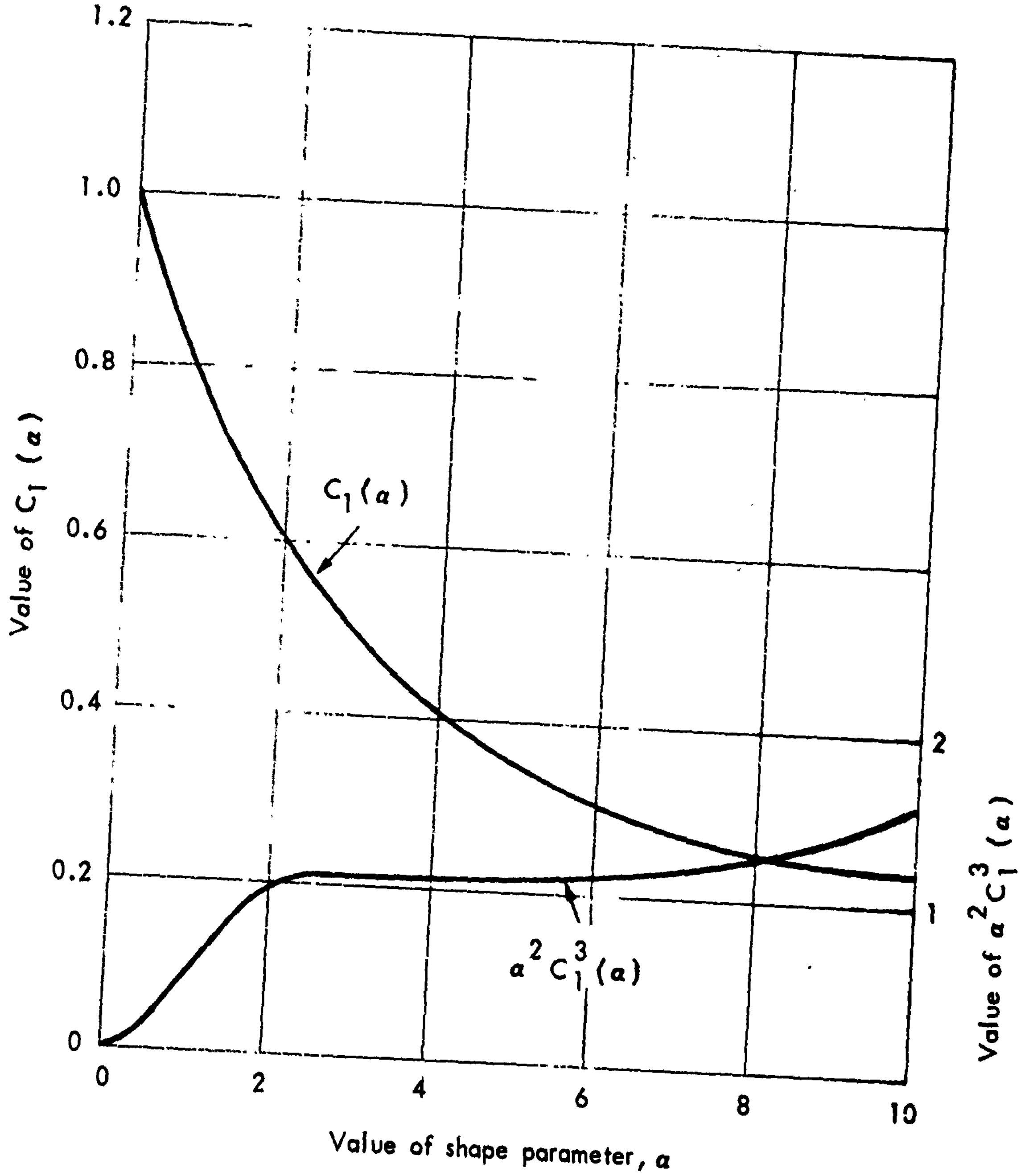

Figure 13 - Functions $C_1(\alpha)$ and $\alpha^2 C_1^3(\alpha)$